Development of a Certification Module tailored to Aircraft Multidisciplinary Design Optimization

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ABSTRACT

At the conceptual design level, Multidisciplinary Design Analysis and Optimization processes are widely used to explore the design space, assess new configurations and identify the most promising family of an air transport aircraft. At these early stages of the design process, the impact of Certification constraints on the main trends is not negligible and thus, it is mandatory to take into account as much information as possible on these aspects to avoid costly redesigns. This paper presents then a prototype of a Certification Module based on a few sections of the CS 25 SUBPART B – FLIGHT published by the European Authorities. This Certification Module that is in fact a digital version of regulatory text is integrated within an advanced Multidisciplinary Design Analysis and Optimization process. This new process can manage a large number of Certification constraints during the optimization of the airframe. More interesting this process allows the optimization some of the CS 25 exit criteria thresholds for a given configuration.

1 INTRODUCTION

The latest civil transport airplanes that are currently flying are the result of a 50 years evolution process based on the "Tube and Wings" configuration. This extreme optimization leads to very limited improvements in the next years if no breakthrough technology is available. Design engineers of the next generation of transport aircraft are then facing a true challenge as the constraints in terms of energy consumption, environmental impact, safety and costs to be taken into account are becoming more and more stringent. For this reason, many studies at the conceptual design aim at identifying disruptive configurations or operational concepts that would offer important potential gains with respect to today's option for different criteria. Among these studies, some focus on disciplinary features while others concentrate on the overall aircraft aspects to address performance assessments for a reference mission. However, for many of these new concepts, issues are not related to a level of performance. The main question is in fact the viability of the proposed solution. And one key aspect of viability is matching Certification requirements. This paper proposes then a Certification Module that is integrated within an Advanced Multidisciplinary Design Analysis and Optimization process. The goal is to verify as early as possible in the exploration of new aircraft concepts that Certifications constraints are met.

In a first section, a classical approach to consider Certification constraints in a design process is presented. Subsequently, an advanced Multidisciplinary Design Analysis and Optimization process featuring the Certification Module is detailed. Last, details on the development of this Certification Module are provided.

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2 CLASSICAL APPROACH TO CONSIDER CERTIFICATION CONSTRAINTS IN AN MDAO PROCESS

To illustrate the classical approach to take into account Certification constraints during a conceptual design loop, this chapter details sizing studies that have been performed in the EU project GABRIEL [1].

2.1 Description of the use case

In this 4 years project (2011-2014) funded by the European Union, a consortium of 12 partners led by REA-Tech proposed an innovative ground-based system that would provide many benefits for future Air Transportation Systems. The main idea consists in using an electro-magnetic levitation system that would provide an extra thrust to the aircraft at take-off. To further enhance the benefits of the system, it is proposed to fully remove the landing gear of the aircraft. The proposed global system would then be decomposed into 4 main components: the aircraft, an electrically powered cart equipped with shock absorbers, the electromagnetic levitation track and its associated sledge. The following figure details ground and air operations based on the GABRIEL concept (left) and a 3D rendering of the concept (right).

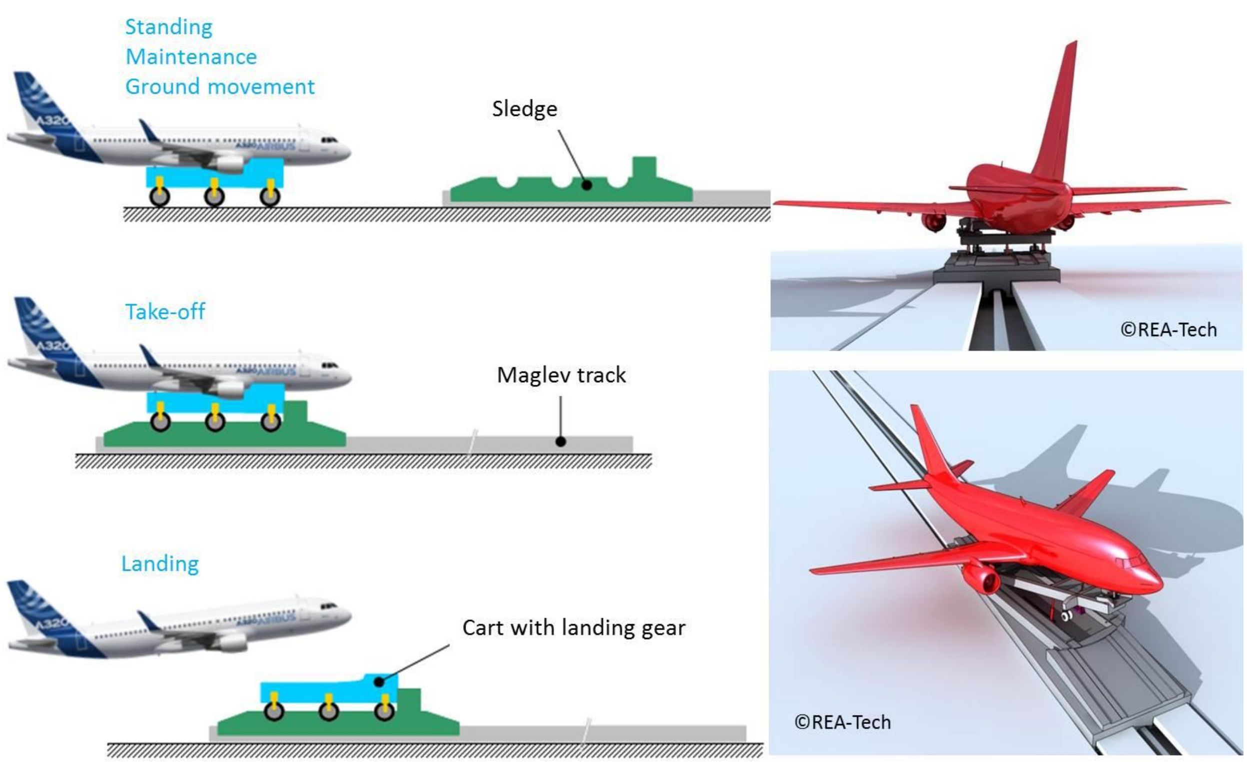

Figure 1 : Presentation of the GABRIEL concept [2]

When standing, for maintenance and ground movements, operations with the GABRIEL concept propose to have the aircraft fixed to an electrically powered cart that is able to provide the classical landing gear functions. For take-off, the aircraft on the cart is transferred along taxi ways up to the Magnetic

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Levitation (MagLev) track following the Tower Ground Controller's guidance. At this point, the cart (and the aircraft) moves into the sledge where a security system locks both systems together. When all checks are performed, the MagLev track provides a horizontal force to the sledge that allows the aircraft to reach lift-off speed. At the end of the mission, the objective is to have the aircraft landing on the cart and sledge. These two components are moving at a given speed that is adapted to the aircraft trajectory. It must be noted the sledge is designed to offer a degree of freedom along an axis that is parallel to the yaw axis to avoid the decrab maneuver. Given all parameters to be monitored during this flight phase, the GABRIEL concept aims for a fully autonomous control of the aircraft with the pilot (in agreement with Terminal Control Area and Tower Runway controllers) providing high level orders to the aircraft.

When reviewing the complete system, the landing removal leads to weight savings and better aerodynamics as the belly fairing can be reduced. In addition the extra thrust provided by the ground system enables the use of smaller engines. Overall, the consortium expects lower fuel consumption on a given mission when using the GABRIEL system with respect to classical take-off and landing operations. Other potential benefits of this disruptive concept are lower noise in the vicinity of the airport and reduced CO_2 and NOx emissions. More information is available on the conclusions of the GABRIEL project in [3].

The project has been divided into Work Packages and Tasks to investigate the concept at both disciplinary and system level to decrease the associated risk, in particular for the landing phase. In addition, demonstrations with unmanned vehicles and a small scale MagLev track took place to further increase the TRL (Technology Readiness Level) of some key technologies. One task in particular focused on the redesign of a twin-engine civil transport aircraft tailored to the GABRIEL concept to assess the benefits in terms of fuel consumption for a reference flight profile. It is during this task that certification constraints have been taken into account in a Multidisciplinary Design, Analysis and Optimization process.

2.2 Overview of the Multidisciplinary Design Analysis and Optimization process

As stated earlier, the use of the GABRIEL concept affects the aircraft on different components and on different disciplines. The objective at this point is to take into account these changes and to assess their impacts at the mission level. To achieve this goal, the proprietary ONERA Multidisciplinary Design, Analysis and Optimization (MDAO) process [4] has been used. Implemented in ModelCenter [5], this process couples all necessary disciplines or systems (that can be seen as modules) for a point mass analysis over a given mission profile. These are Aerodynamics, Propulsion, Structure / weight and Performance. In addition, there are two other modules that provide input to all the others: Geometry and Atmosphere. The complete MDAO process is driven by a set of design variables that define the airplane configuration as well as the mission profile. Subsequently, in order to define the most suitable geometry, the analysis provides a consistent aircraft weight breakdown coupled with an optimizer following the Multi-Disciplinary Feasible (MDF) formulation. More details on the modules are provided in the project deliverable dedicated to the analysis and optimization process [6].

Given the characteristics of the GABRIEL system and its impact of the aircraft, it is important to note that the different modules have been modified to meet certain specifications. In the case of the performance module, it has been necessary to take into account the extra-thrust provided by the MagLev track during take-off. For Aerodynamics, the code has been modified in order to modify the drag coefficient to model the belly fairing removal. At this stage of the project, high fidelity analyses with Computational Fluid Dynamics (CFD) tools have been made to assess in an accurate manner the associated changes in the aerodynamic coefficients. For Structure / weight, as the landing gear is replaced by simple struts which

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will lock into the cart on the moving sledge, the weight module has been revised to take into account weight variations associated to necessary structural reinforcements and systems removal. Last but not least, the MDAO process features a second mission (in addition to the sizing one) to make performance assessments of an aircraft that has the same Operating Empty Weight but that flies a mission with a different range. In this manner, fuel consumptions are directly comparable. The figure here below illustrates the modified MDAO process under interest:

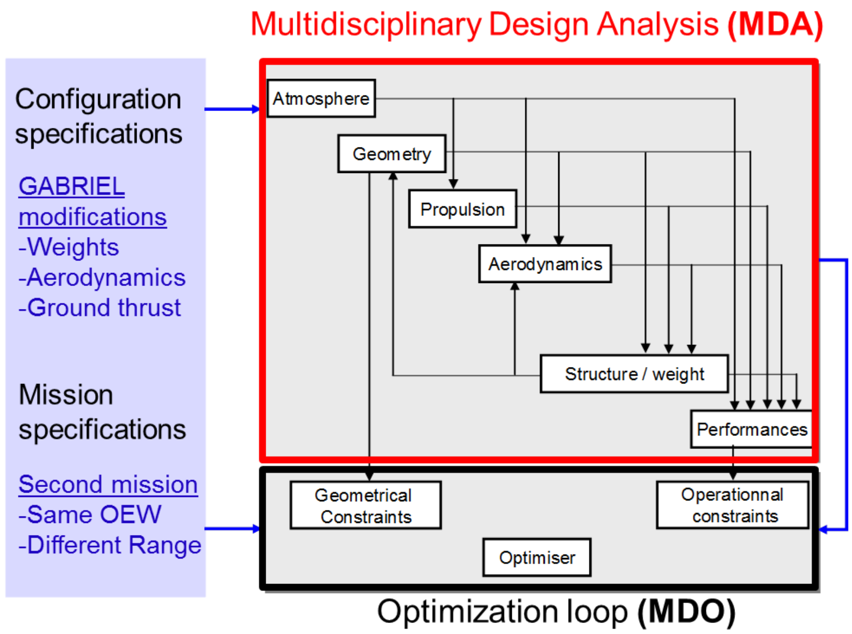

Figure 2 : Overview of the MDAO process used in the GABRIEL project

As the ground based system based on the MagLev track can provide an important additional amount of thrust to the aircraft during ground run, the engine size is no more constrained by the take-off field length. This key parameter becomes then solely driven by the Certification constraints (Performance) provided in CS 25 published by EASA (European Aviation Safety Agency) [7].

2.3 Taking into account certification and operational constraints

The CS 25 indicates clear requirements in terms of climb capacity in One Engine Inoperative condition as well as All Engine Operative cases. Thus, the Performance module has been further modified in order to verify during the sizing and optimization loops that these constraints are met. As the verification is based on a simple performance analysis of the climb condition that corresponds to a non-linear system, a routine has been written in Fortran in order to calculate the resulting climb gradient at key steps of the mission given the following set of parameters (extracted from CS 25): thrust setting, flap configuration, landing gear (Retracted or Extended), Speed, Weight, Altitude. This routine is then used for three Certification constraints and one operational requirement:

- CS 25.119 Landing climb: all-engines operating;
- CS 25.121 (b) Climb: one-engine inoperative (Take-off; landing gear retracted);

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- CS 25.121 (d) Climb: one-engine inoperative (Approach);
- Service ceiling of 500 ft/min at the highest cruise point.

In all cases, resulting gradients or rates of climb calculated by the Performance module are written in an output file that is used during the sizing and optimization process.

2.4 Implementation in ModelCenter and results

The process shown in Figure 2 is implemented in ModelCenter [5], a design environment that can easily couple executables programs, Python scripts and Excel spreadsheets. Figure 3 illustrates on the left side the inputs that can be set by the design team and on the right side, the sizing process can be observed (boxes with symbol "+" represents a group of sub-modules).

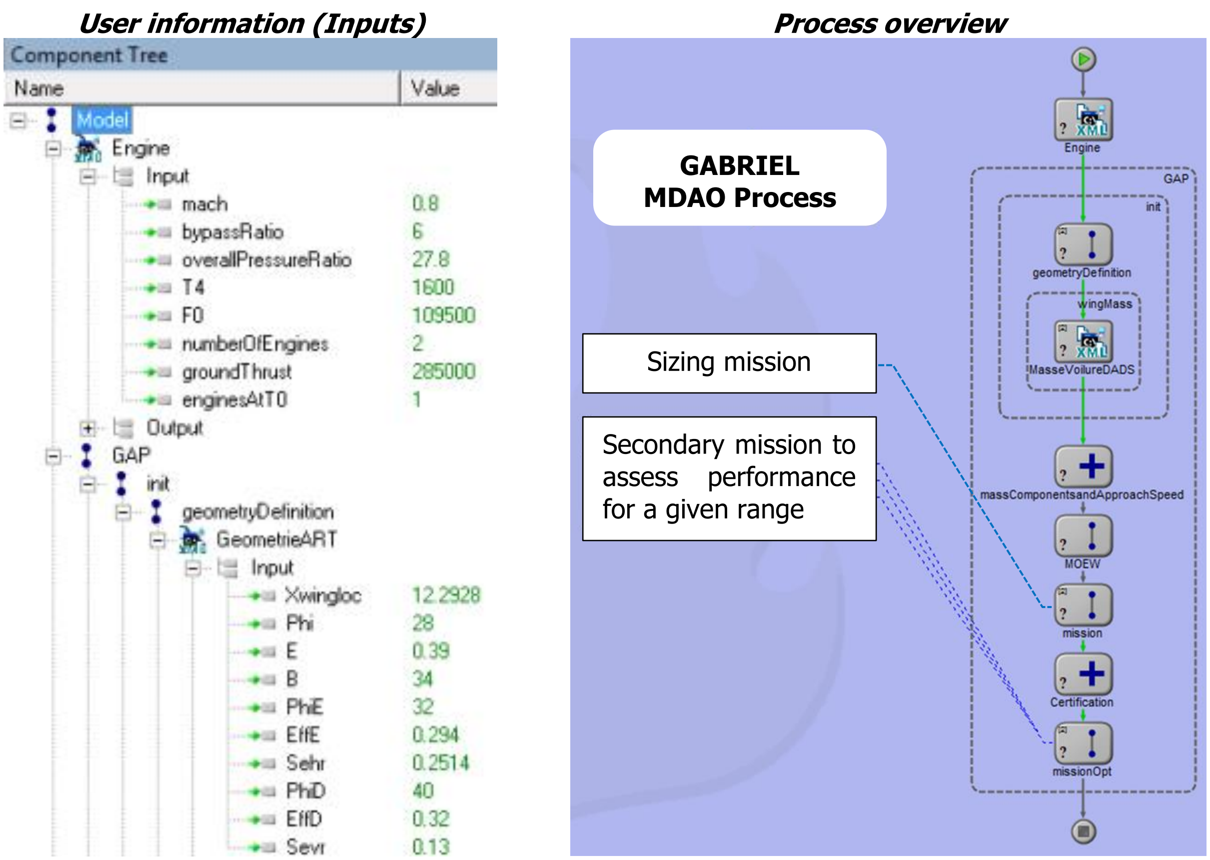

Figure 3 : GABRIEL MDAO Process implemented in ModelCenter [6]

Regarding the inputs that can be set by the users, they are divided into two groups. The first one concerns both the turbine engines and the ground based system that is defined by two values used during the take-off analysis: the thrust provided by the MagLev track and a flag indicating the thrust level of the engines during the ground run (in Figure 3, the value is set to 1, meaning full thrust). The second group corresponds to the geometrical definition of the airframe.

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As this paper concentrates on how the Certifications and operational constraints have been taken into account in the MDAO process, Figure 4 details the Certification box within the process and its associated User information.

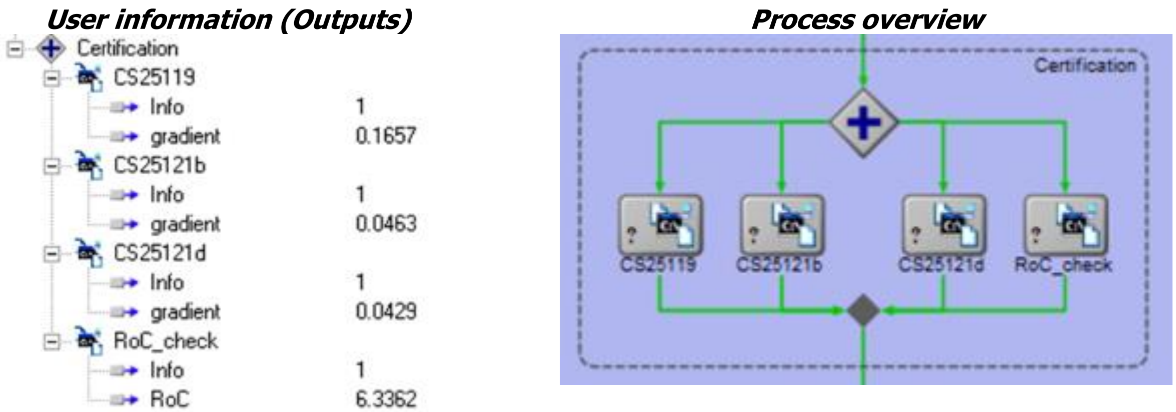

Figure 4 : Expanded view of the Certification box

As last step in the MDAO process, the Certification and operational constraints are checked for specific points of the mission for a consistent aircraft (converged masses). For the three Certification sections/paragraphs and the operational limitation taken into consideration in this study, ModelCenter [5] opens the resulting file from the Fortran routine and assigns the value of the exit criteria to be monitored (in this case the climb gradient or the Rate of Climb) to variables. During the optimization process, the algorithm checks these variables to make sure that the final solution meets the value indicated by regulations. In addition to this exit criteria value, the left part of Figure 4 provides for each Certification and operational constraint an “Info” value. This is an output of the non-linear solver that indicates if calculations converged to a final solution without issue (the value of 1 indicates such positive condition). In this manner, the design team can rapidly check within the feasible solutions if one or more are the result of a bad convergence by the non-linear solver.

As the full MDAO process was implemented, a validation step has been made through the test of a reference aircraft with known consumption data over a detailed mission profile. Since the results were good (difference of -2.7% in the Operating Empty Weight and +1.8% in the fuel consumption with respect to the reference case), the process has been subsequently used for two distinct assessments:

- Assess the benefits in terms of fuel consumption of the various changes associated to the GABRIEL concept on the reference aircraft;
- Explore the design space to define a family of most promising concepts taking this time into account wing planform modifications as well as the associate resizing of the airframe.

Complete analyses of these two studies are presented in details in [6] and won’t be reported here. However, as certification is of key importance in this paper, the multi-objective optimization history for the second task is presented in this paragraph. To have a better understanding of this overall optimization goal, it must be recalled that the design variables available to the design team were the main wing span, the leading edge sweep angle, the external taper ratio and the engine maximum thrust. To identify the most promising family of resized airplanes, the multi-objective function was minimization of the Maximum Take-Off Weight and minimization of the Total Fuel Weight. For the constraints taken

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into consideration, the approach speed has been added to the four Certification and operational constraints presented in the previous chapter. The results provided by ModelCenter [5] illustrated in Figure 5 were really interesting as they showed the impact of just four constraints on the Pareto front defining the best families of vehicles. The Pareto front is moved if the solutions which do not satisfy the constraints are identified (unfeasible solutions in red in Figure 5).

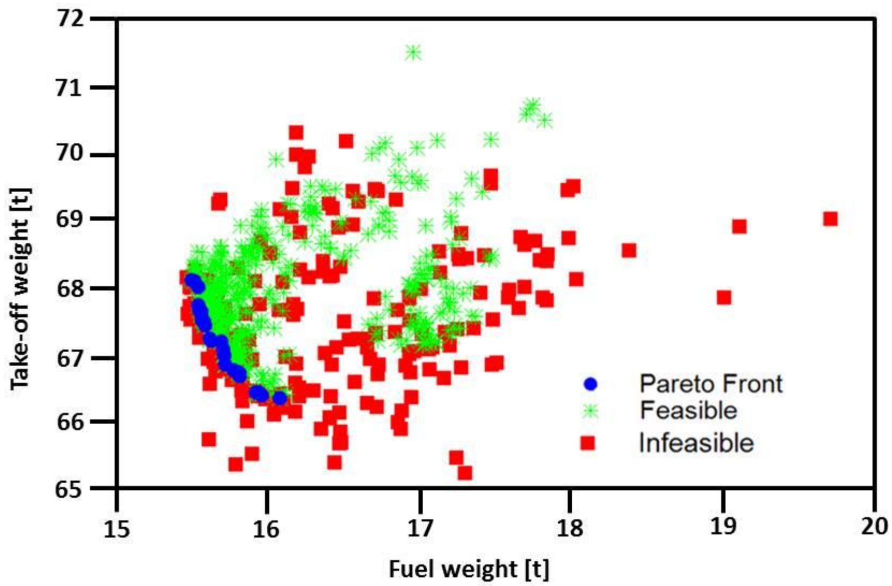

Figure 5 : Optimization history for a multi-objective optimization taking into account certification constraints

It can be thus concluded that Certification aspects must be taken as soon as possible in the design process to make sure that the optimization is converging to a feasible solution. Also, as only four constraints at the performance level have such an influence, the question about how to take more into account becomes a point of interest.

3 AN ADVANCED MDAO PROCESS

3.1 Limitations of the current approach

As stated in the last paragraph of the previous chapter, the next challenge for the MDAO process is to be able to take into account more Certification and operational constraints. In order to address this point, the authors reviewed the regulatory text CS 25 – SUBPART B FLIGHT to gather as many information as possible. This analysis leads to the identifications of three limitations of the current approach:

- First, it must be explained that within SUBPART B, not only Performance constraints are detailed but also Controllability and Manoeuvrability as well as Stability requirements are indicated. In Figure 6, the section CS 25.145 is shown:

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CS 25.145 Longitudinal control

(a) (See AMC 25.145(a).) It must be possible at any point between the trim speed prescribed in CS 25.103(b)(6) and stall identification (as defined in CS 25.201(d)), to pitch the nose downward so that the acceleration to this selected trim speed is prompt with –

(1) The aeroplane trimmed at the trim speed prescribed in CS 25.103(b)(6);

(2) The landing gear extended;

(3) The wing-flaps (i) retracted and (ii) extended; and

(4) Power (i) off and (ii) at maximum continuous power on the engines.

Figure 6 : Section CS 25.145 Longitudinal control

In this section, the requirement clearly states that an assessment of the moment around the Center of Gravity must be made to verify Pitch capabilities. At the MDAO process level, it means that the point mass analysis used in the Performance module is not sufficient anymore. An analysis based on a six degrees of freedom becomes mandatory.

- The second point is related to the newest civil transport airplanes such as the A380. A review of the Special Conditions issued for the Airbus A380-800 airplane in the frame of the FAA (Federal Aviation Administration) certification [8], it can be seen that the airplane has a neutral static stability within the normal operational envelope. The MDAO process should then be capable of handling configurations that could be both stable and unstable. For the latest, the sizing of the aircraft could then require the use of a Flight Control System (FCS).

- The third and last point that has been observed during the review of CS 25 SUBPART B – FLIGHT is highlighted in CS 25.145 (Figure 6). In this section, the complexity of the regulatory text is shown as this single section refers to many disciplines and also to many other sections. To translate these different links within the current structure of the MDAO process where certification constraints are treated at the disciplinary or system level would require an important number of interdependencies and updates related to reference values of the sections (speed for example) would be difficult to be implemented.

As the GABRIEL project aimed at increasing the TRL of a new Air Transport System, the consortium also explored in a very preliminary way the necessary changes that could be made to Certification to have such system operational [9]. One aspect that stood out was that the current regulatory texts are - as expected to maximize safety - really stringent in terms of design options and innovative features can be treated through the addition of Critical Review Items. When exploring the design space associated to a new aircraft configuration with the MDAO process, there is thus another natural limitation that is directly linked to the available Certification Specifications. The next paragraph presents a new MDAO process that features possible answer to these limitations.

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3.2 A two-ways optimization

The first change proposed within the MDAO process is an evolution of the Aircraft MDA as new modules are taken into account. First, instead of the Performance module, a full simulator based on a six degrees of freedom model is used. More details about the choice of selecting a full simulator instead of a basic six degrees of freedom model are given in [10]. Second, as flight dynamics aspects are influenced by inertial properties, a new dedicated module is integrated. Last but not least, a Flight Control System (FCS) can be modeled within the full simulator to explore unstable configurations. At the highest level of the MDAO process, the design team can therefore influence the Handling Qualities of the airplane as the FCS characteristics are implemented as Design Variables.

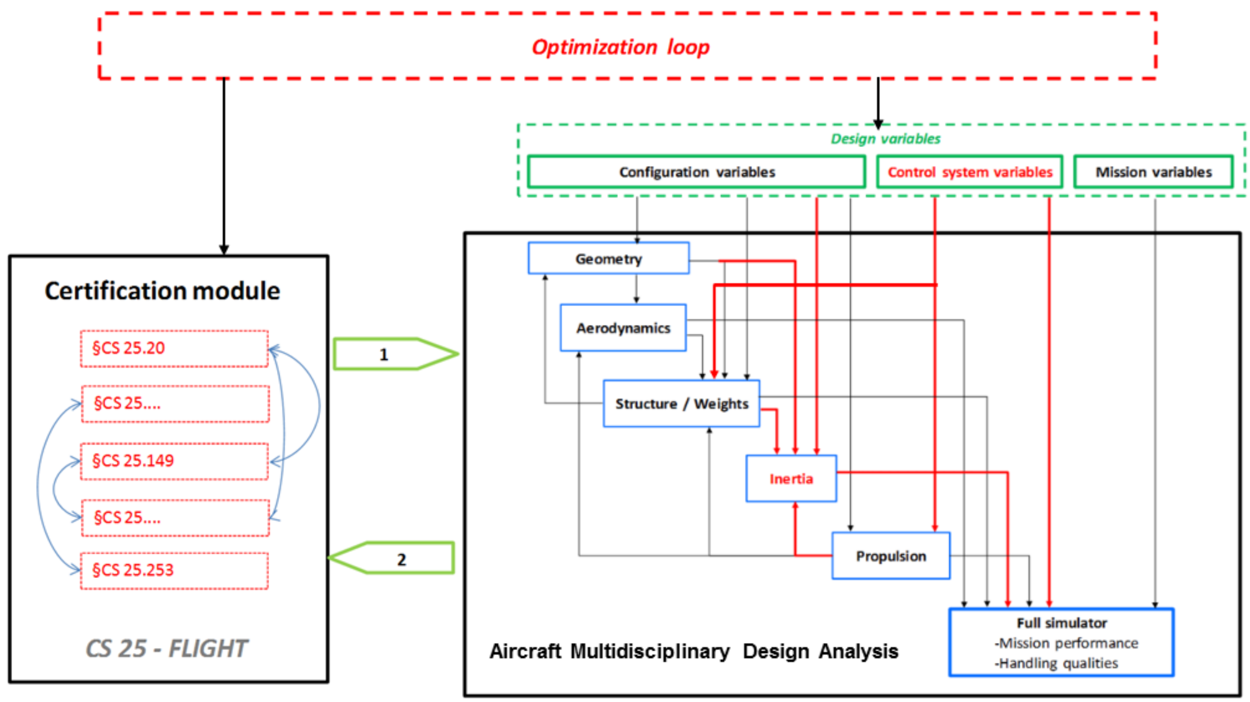

Figure 7 : The Advanced MDAO process with an external Certification Module

The second major change that is proposed is the definition of a Certification Module. This external module is in fact a digital version of the CS 25 SUBPART B – FLIGHT where all the different links between the sections are identified and reference value changes are automatically propagated to all sections. The principal idea behind such module is the possibility to directly use this format of the regulatory text in the optimization process. The interesting part is that given this set-up, optimizations can be performed in two ways:

- Way 1 in Figure 7: The design team selects a number of Design Variables and the MDAO process focuses on defining the most promising aircraft for a given set of Certification constraints defined in the Certification Module;
- Way 2 in Figure 7: This time, the aircraft configuration is fixed and the optimizer will determine the exit criteria thresholds for the various sections of interest of the Certification Module. It is believed that this approach will be paving the way for step by step Certification Specifications changes [11] to better allow the study of new concepts.

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4 DEVELOPMENT OF THE CERTIFICATION MODULE

4.1 CS 25 SUBPART B – FLIGHT sections review

In order to generate the Certification Module based on CS 25 SUBPART B – FLIGHT, a careful review of the associated sections has been completed. The goal was to identify the overall structure and understand the main logic. It must be noted that a first distinction is already made within the regulatory text where sections are divided by topic. The most important ones for SUBPART B – FLIGHT are:

- Performance, described from CS 25.101 to CS 25.125
- Controllability and Manoeuvrability, described from CS 25.143 to CS 25.149
- Stability, described from CS 25.171 to CS 25.181

CS 25.119 Landing climb: all-engines-operating

In the landing configuration, the steady gradient of climb may not be less than 3·2 %, with the engines at the power or thrust that is available 8 seconds after initiation of movement of the power or thrust controls from the minimum flight idle to the go-around power or thrust setting (see AMC 25.119); and

(a) In non-icing conditions, with a climb speed of V_{REF} determined in accordance with CS 25.125(b)(2)(i); and

(b) In icing conditions with the most critical of the "Landing Ice" accretion(s) defined in Appendices C and O, as applicable, in accordance with CS 25.21(g), and with a climb speed of V_{REF} determined in accordance with CS 25.125(b)(2)(ii).

[Amdt No: 25/3]

[Amdt No: 25/16]

Configuration

Flight Condition

Exit criteria

CS 25.147 Directional and lateral control

(a) *Directional control; general.* (See AMC 25.147(a).) It must be possible, with the wings level, to yaw into the operative engine and to safely make a reasonably sudden change in heading of up to 15° in the direction of the critical inoperative engine. This must be shown at 1·3 V_{SR1}, for heading changes up to 15° (except that the heading change at which the rudder pedal force is 667 N (150 lbf) need not be exceeded), and with –

(1) The critical engine inoperative and its propeller in the minimum drag position;

(2) The power required for level flight at 1.3 V_{SR1}, but not more than maximum continuous power;

(3) The most unfavourable centre of gravity;

(4) Landing gear retracted;

(5) Wing-flaps in the approach position; and

(6) Maximum landing weight.

Figure 8 : Examples of CS 25 sections

In addition to evaluate the differences, the review phase has been equally important to point out common points between the various sections and their constraint description. After several iterations, a possible decomposition of the sections is presented in Figure 8 for two cases (one related to Performance, the other one related to Controllability and Manoeuvrability). For both constraints, the section indicates exit criteria that must be achieved given information about the configuration and the flight conditions. This preliminary structure has been used to generate a Unified Modeling Language (UML) of CS 25 SUBPART B – FLIGHT presented in the next section.

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4.2 An UML model for CS 25 – SUBPART B FLIGHT data description

The resulting UML model for the data description of CS 25 – SUBPART B FLIGHT is presented on the next figure.

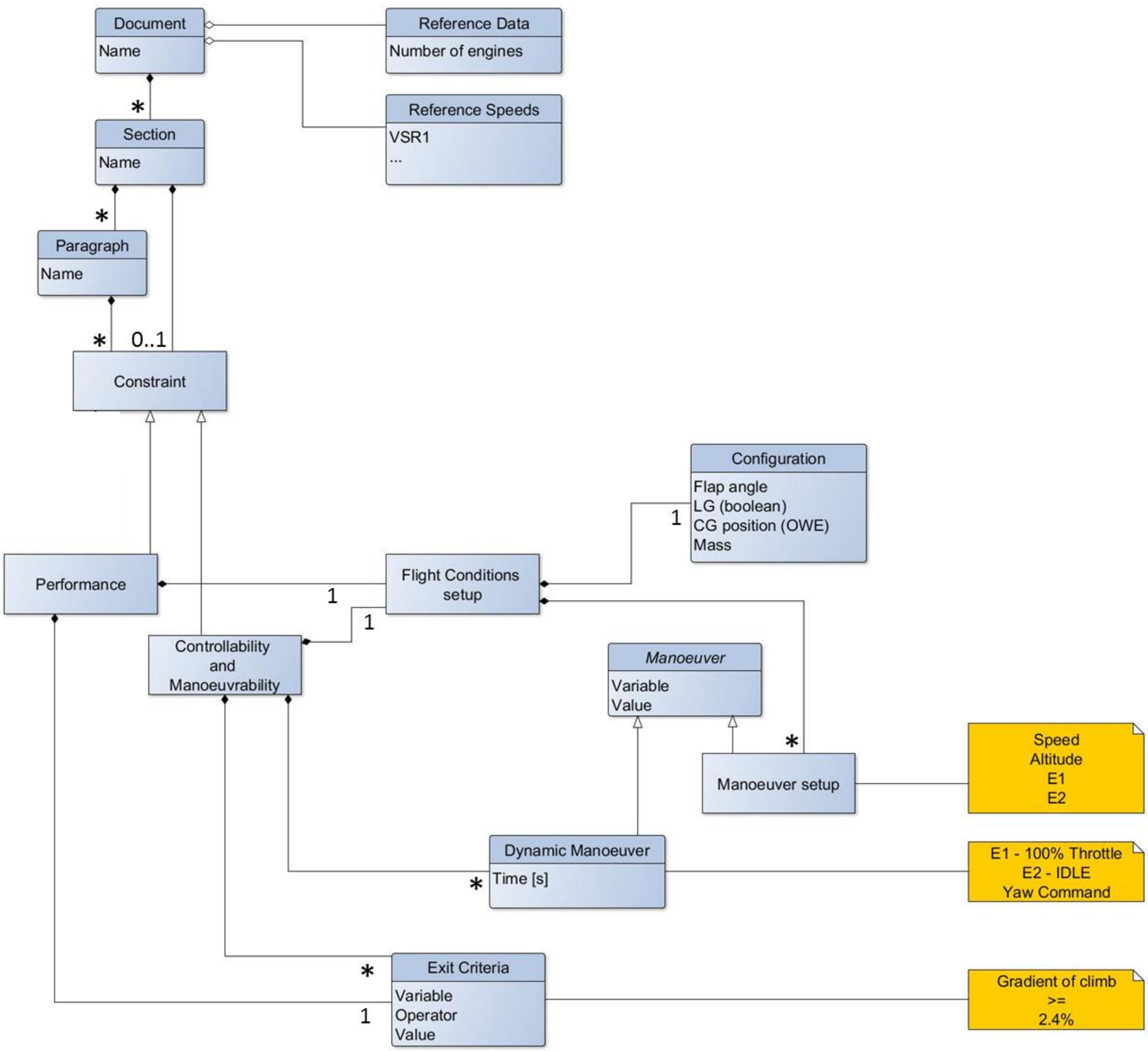

Figure 9 : UML description of CS 25 – SUBPART B FLIGHT

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This UML model must be interpreted in the following manner: the document (CS 25 SUPART B – FLIGHT) has many sections and it references to two lists of key high level parameters of the regulatory text. These sections can have Paragraphs that have Constraints. It can also happen that there aren't Paragraph as in the case of CS 25.119. Then, these Constraints can be of two types in this preliminary prototype of the Certification Module: Performance or Controllability and Manoeuvrability. Both types of Constraints have as expected Exit Criteria as well as Flight Conditions setup. Naturally, for the Performance Constraints, the Flight Conditions setup has Configuration information as well as Manoeuver setup. On the other hand, the Controllability and Manoeuvrability Constraints have Dynamic Manoeuvers where changes on the aircraft state with respect to time are indicated. To simplify the overall structure, it is then proposed to have Manoeuver setup and Dynamic Manoeuvers as types of Maneuvers, a higher level component that manages many parameters.

With such a generic description of the CS 25 SUPART B – FLIGHT, the authors used subsequently the tool GAMME to generate the Certification Module.

4.3 GAMME description

GAMME (Génération Automatique par Méta-Modèle Enrichi) is an in-house tool based on Model-Driven Engineering [12]. It has been developed to answer the need for data unification in simulation modeling, especially in the field of complex systems where several forms of the same data may be used. At the center of GAMME, there is a metamodel that allows the description of data models in an object-oriented manner. Subsequently, the data models are transformed into various software components such as C++, Java, Python classes, XML, JSON serializers or User Interface elements. One of the key asset is the automated update of all software components following changes in the data model and consequently the possibility of rapidly prototyping while ensuring consistency between the different components. The next figure illustrates the flow diagram in GAMME.

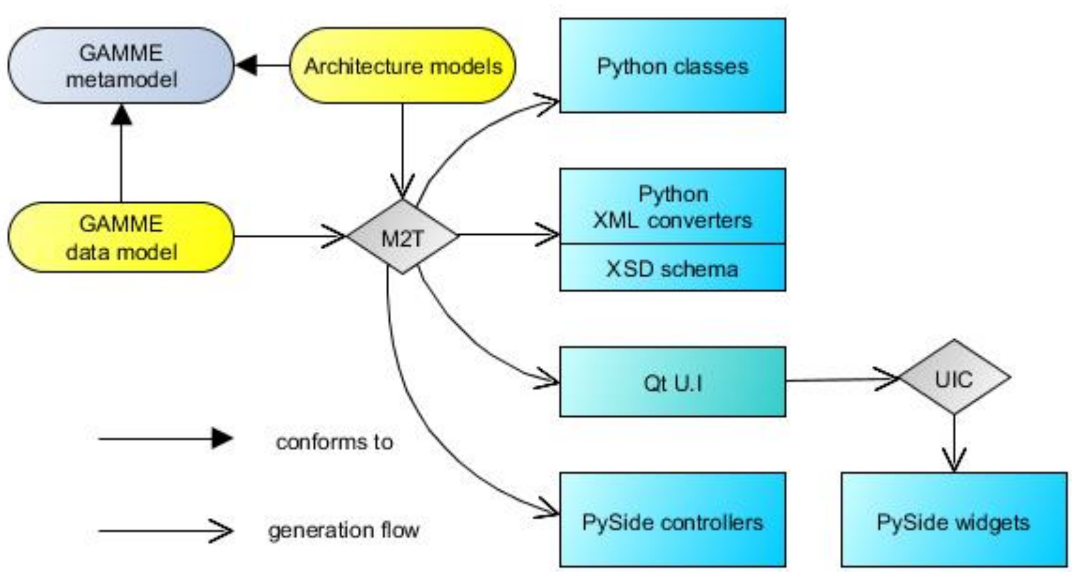

Figure 10 : Overview of GAMME flows in the context of this paper

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4.4 Graphical User Interface to build the Certification Module

In the case of the Certification Module, the UML description of sections related to Subpart B- FLIGHT of the CS 25 is translated into a data model that conforms to the GAMME metamodel. Through the automatically generated Graphical User Interface components, it is possible to enter all data included in the regulatory text. In the end, all the generated information is stored in an .XML file that is the main part of the Certification Module and that can be used during optimization loops. Figure 11 here below shows the GUI for different levels and different constraints of the Certification Module.

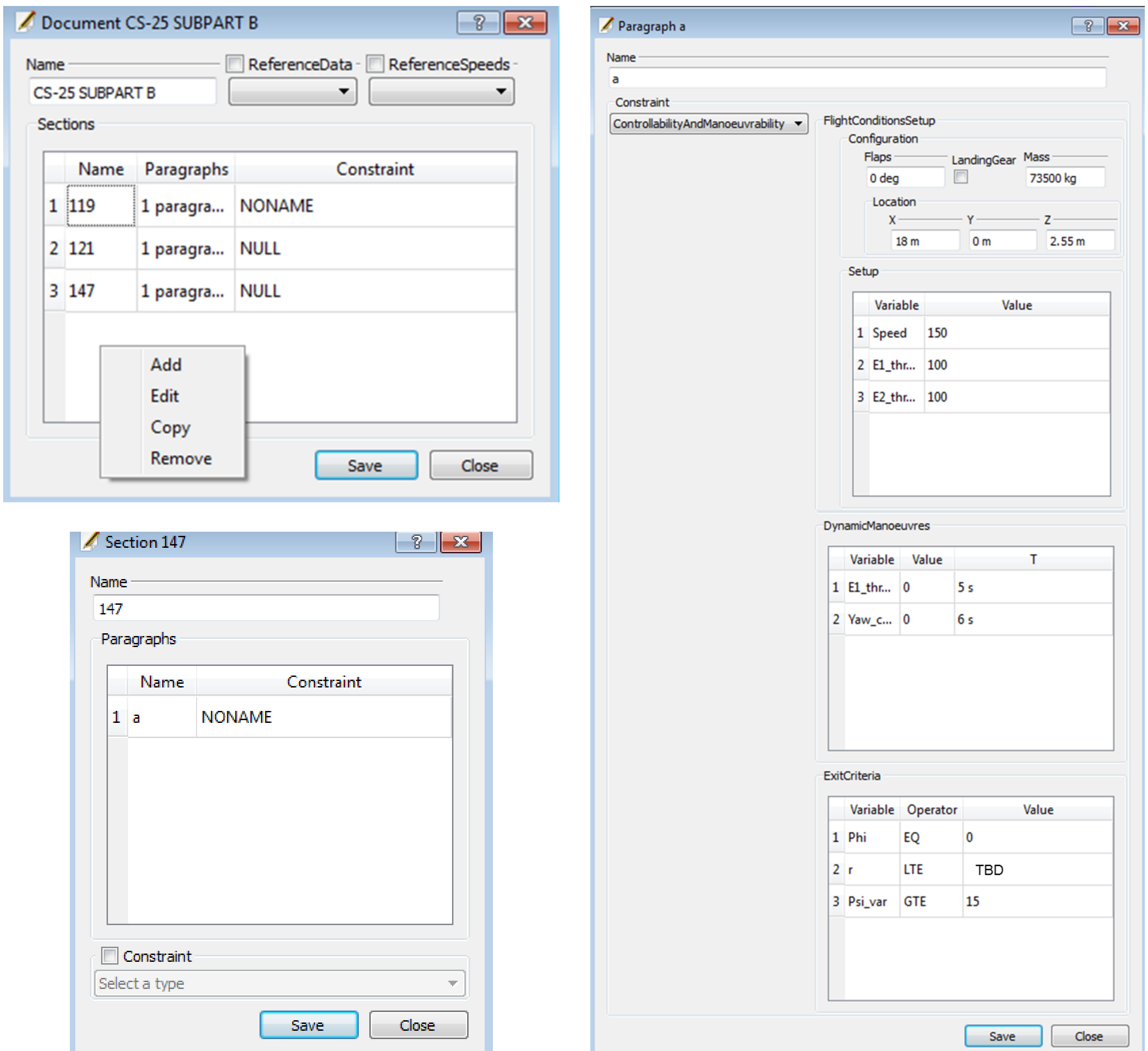

Figure 11 : Example of the GUI to build the Certification Module

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In the first image of the left column in Figure 11, the name of the document to be numerically modeled is identified (CS 25 SUBPART B). Three sections have been easily added through the GUI and one of them, the CS 25.119, has a constraint (NONAME, opposed to NULL when the constraint is not defined) that isn't related to a paragraph. In the second image of the left column in Figure 11, focus is made on section CS 25.147 that has a constraint in Paragraph a. In the right column of Figure 11, all necessary data to verify the constraint are shown. The first elements of the Flight Condition Setup to be provided are the ones related to the configuration (flap, CG position, landing extracted or retracted, weight). In a second step, the initial flight conditions are specified. As CS 25.147 is a Controllability and Manoeuvrability constraint, the dynamic manoeuvers are described by providing changes in the aircraft state with respect to time. Finally, the exit criteria and their associated threshold value are provided. Following this translation of the CS 25 into the GUI, a numerical version of the text is available in a .XML format that can be used in the advanced MDAO process.

5 CONCLUSION

Studies carried out at Onera about taking into account the Certification constraints in early phases of the design process emphasized at first how these requirements modify the resulting Pareto plots during multi-objective optimizations. Subsequently, as a number of limitations have been identified regarding the existing design processes and the integration of Certification constraints, an advanced Multidisciplinary Design Analysis and Optimization process has been proposed. With the analysis based on a full simulator, many constraints associated to stability, Controllability and Manoeuvrability can now be considered during optimizations. Also, the process can now assess unstable configurations as Handling Qualities are kept at a desirable level through the Flight Control System. In this manner, the design space becomes automatically bigger.

To complement this new overall process, the authors developed a prototype of the Certification Module that is a digital version of the regulatory texts. Following a review of the CS 25 SUBPART B – FLIGHT, a UML model of the certification has been defined to clearly identify the Certification structure and links. Through the Onera tool GAMME, software components based on the CS 25 have been developed and the resulting .XML file can be directly used in an Analysis and Optimization process.

Also, it is important to note that with the separation of this Certification Module from the Multidisciplinary Design Analysis, optimizations can be performed in two distinct manners: on one hand, the airframe is optimized taken into account certification constraints. In the other hand, the exit criteria threshold can be determined for given aircraft geometries. Such an approach could be the initial point of a step by step approach towards the CS 25 adaptation to consider disruptive configurations.

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